

Hot Topics from Belle

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The most precise current determination of the Unitarity Triangle angle ϕ_3 is presented. It is obtained using the decay $B^+ \rightarrow D^{(*)}K^+$, with Dalitz plot analysis of the subsequent $D \rightarrow K_S\pi^+\pi^-$ decay. The result is $\phi_3 = 68^\circ_{-15^\circ}^{+14^\circ}(\text{stat}) \pm 13^\circ(\text{syst}) \pm 11^\circ(\text{model})$.

1 Introduction

The year 2004 has seen a great number of important new results from Belle. Studies of time-dependent asymmetries in $B \rightarrow \pi^+\pi^-$ revealed the second observation of CP violation, and the first evidence for direct CP violation, in the B system [1]. More recently, further evidence for direct CP violation has been found in $B \rightarrow K^-\pi^+$ decays; this effect is also seen by BaBar [2]. The decay $B \rightarrow \pi^0\pi^0$ is now observed with more than 5σ [3], and evidence for $B \rightarrow \rho^0\pi^0$ has been seen [4]. Studies of new particles observed at Belle have stimulated theoretical interest [5], and further excitement has been aroused by new results on the time-dependent asymmetries in $b \rightarrow s$ penguin transitions [6]; new results on $B \rightarrow K_SK_SK_S$ and $B \rightarrow K_S\pi^0\gamma$ were shown for the first time in FPCP2004 [7]. To complete this brief selection of the many other new results from Belle [8], the first studies of the forward-backward asymmetry in $B \rightarrow K^*l^+l^-$ have been performed [9].

This plethora of new results is made possible by the excellent performance of the KEKB accelerator. KEKB is an asymmetric-energy e^+e^- (3.5 GeV on 8 GeV) collider [10], operating at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV) with a peak luminosity that exceeds $1.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. At the time of FPCP2004, the total integrated luminosity was approaching 300 fb^{-1} (at the time of writing it is approaching 330 fb^{-1}), however the results presented here use the data sample of 253 fb^{-1} accumulated by summer 2004, corresponding to approximately 275×10^6 $B\bar{B}$ pairs.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [11]. Two different inner detector configurations were used. For the first sample of 152 million $B\bar{B}$ pairs, a 2.0 cm radius beampipe and a 3-layer silicon vertex detector were used; for the latter 123 million $B\bar{B}$ pairs, a 1.5 cm radius beampipe, a 4-layer silicon detector and a small-cell inner drift chamber were used [12].

2 Principles of ϕ_3 Extraction from $B^+ \rightarrow D^{(*)}K^+$

The main objective of the B factories is to make precise measurements of the elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [13]. As is well known, the unitarity of the CKM matrix results in the expression

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0, \quad (1)$$

which can be represented as a triangle in the complex plane (the so-called Unitarity Triangle). Two popular (and various other less popular) sets of names for the angles of this triangle are used,

$$\phi_1 \equiv \beta = \arg \left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right], \quad \phi_2 \equiv \alpha = \arg \left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right], \quad \phi_3 \equiv \gamma = \arg \left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right]. \quad (2)$$

It has long been known that decays of the type $B \rightarrow DK$ are sensitive to ϕ_3 [14], and various methods using different final states of the neutral D meson have been proposed [15]. These are based on two key observations: neutral D^0 and \bar{D}^0 mesons can decay to a common final state, and the decay $B^+ \rightarrow D^{(*)}K^+$ can produce neutral D mesons of both flavours via $\bar{b} \rightarrow \bar{c}u\bar{s}$ and $\bar{b} \rightarrow \bar{u}c\bar{s}$ transitions, with a relative phase θ_+ that depends on both strong and weak phase differences between the two amplitudes, $\theta_+ = \delta + \phi_3$. For the charge conjugate mode, the relative phase is $\theta_- = \delta - \phi_3$. The size of possible CP violation effects depends on the ratio of the magnitudes of the interfering amplitudes, which we denote by r .

Recently, three body final states common to D^0 and \bar{D}^0 , such as $K_S\pi^+\pi^-$ [16], were suggested as promising modes for the extraction of ϕ_3 . The principle of the technique is as follows (for more details see [17]). We define the amplitude for $\bar{D}^0 \rightarrow K_S\pi^+\pi^-$ at a point on the Dalitz plot given by (m_+^2, m_-^2) to be $f(m_+^2, m_-^2)$, where m_+^2 and m_-^2 are the squared invariant masses of $K_S\pi^+$ and $K_S\pi^-$, respectively. Assuming CP invariance in D meson decay, the corresponding amplitude for D^0 decay is then $f(m_-^2, m_+^2)$. The amplitude for $B^+ \rightarrow DK^+$ can then be written as $f(m_+^2, m_-^2) + re^{i(\delta+\phi_3)}f(m_-^2, m_+^2)$, while that for $B^- \rightarrow DK^-$ is $f(m_-^2, m_+^2) + re^{i(\delta-\phi_3)}f(m_+^2, m_-^2)$. Thus, once the D decay model f is fixed, the values of r , ϕ_3 and δ can be determined by simultaneously fitting data from B^+ and B^- decays.

The same arguments also apply to similar decays such as $B^+ \rightarrow D^*K^+$. Some care must be taken, since for each B decay mode the values of r and δ can be different. It has recently been pointed out that for $B^+ \rightarrow D^*K^+$ there is an effective shift of π in the value of δ between the cases that the decays $D^* \rightarrow D\pi^0$ and $D^* \rightarrow D\gamma$ are used [18].

The D decay distribution can be measured at B factories using the large samples of flavour tagged D mesons produced in $D^+ \rightarrow D^0\pi^+$ (and charge conjugate) decays following continuum $e^+e^- \rightarrow c\bar{c}$ reactions. However only $|f(m_+^2, m_-^2)|^2$ can be measured resulting in some uncertainty due to the model assumed to describe the phase variation across the Dalitz plot.

This technique was first implemented by Belle, using a 140 fb^{-1} data sample, to obtain $\phi_3 = 77^\circ \pm_{19^\circ}^{+17^\circ}(\text{stat}) \pm 13^\circ(\text{syst}) \pm 11^\circ(\text{model})$ [19]. Recently the same method has been used by BaBar, with a data sample of $211 \times 10^6 B\bar{B}$ pairs, to obtain $\phi_3 = 88^\circ \pm 41^\circ(\text{stat}) \pm 19^\circ(\text{syst}) \pm 11^\circ(\text{model})$ [20].

The results presented below are preliminary updates of the previous Belle analysis. More details can be found in [21].

3 Dalitz analysis

3.1 Extraction of D Decay Model

We select candidates for the $D \rightarrow K_S \pi^+ \pi^-$ decay, and combine with slow charged pions (π_s^\pm) to make $D^{*\pm}$ candidates. We require $D^{*\pm}$ candidates to have momenta above $2.7 \text{ GeV}/c^2$ in the centre of mass (cm) frame to reject background from B decay. We fit the mass difference $\Delta M = M_{K_S \pi^+ \pi^- \pi_s^\pm} - M_{K_S \pi^+ \pi^-}$ to obtain signal and background fractions, and then require $144.6 \text{ MeV}/c^2 < \Delta M < 146.4 \text{ MeV}/c^2$. The distribution of background events across the Dalitz plot is obtained from a sideband region of ΔM . We then fit the candidates to a model including the components listed in Table. 1, with efficiency, resolution and background taken into account. The result of the fit is shown in Fig. 1. The χ^2/ndf of the fit is 2543/1106, however fine tuning the model has little effect on ϕ_3 and possible discrepancies are taken into account in the model uncertainty.

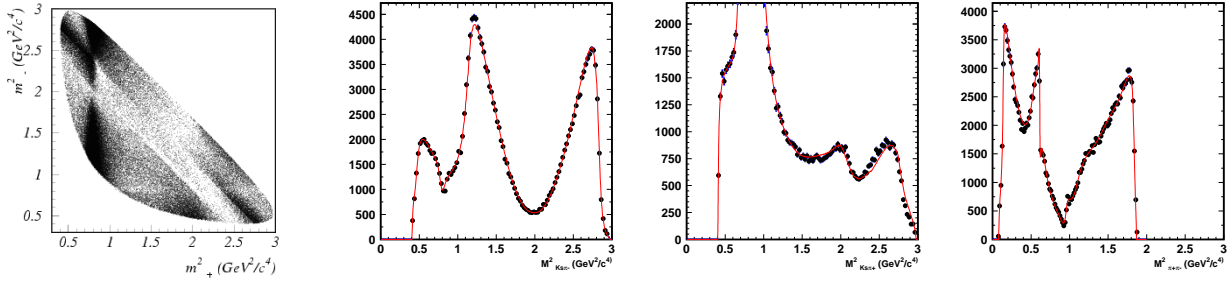


Figure 1: From left to right: Dalitz plot distribution of tagged D decays; projections onto the m_{-}^2 , m_{+}^2 and $m_{\pi^+\pi^-}^2$ variables.

3.2 Selection of B Decay Candidates

We reconstruct neutral D mesons in the $D \rightarrow K_S \pi^+ \pi^-$ mode, and D^* mesons by making combinations with π^0 candidates. We then combine these with prompt tracks, which are selected as kaon candidates on the basis of information from the CDC, TOF and ACC systems. The selection of B candidates is based on the CM energy difference $\Delta E = \sum E_i - E_{\text{beam}}$ and the beam-constrained B meson mass $M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - (\sum p_i)^2}$, where E_{beam} is the CM beam energy, and E_i and p_i are the CM energies and momenta of the B candidate decay products. The requirements for signal candidates are $5.272 \text{ GeV}/c^2 < M_{\text{bc}} < 5.288 \text{ GeV}/c^2$ and $|\Delta E| < 0.022 \text{ GeV}$. The signal and background fractions are obtained from binned fits to the ΔE distributions, which are shown in Fig. 2. The signal is modelled with a Gaussian, an additional Gaussian is used to describe the background from $B^\pm \rightarrow D^{(*)} \pi^\pm$ with the prompt pion misidentified as a kaon, that peaks at $\Delta E \sim 50 \text{ MeV}$. The remaining background is modelled by a linear function. For $B^\pm \rightarrow DK^\pm$ the selection efficiency is 11%, there are 276 candidates satisfying all selection criteria of which 209 ± 16 are found to be signal events. For $B^\pm \rightarrow D^* K^\pm$

| Resonance | Amplitude | Phase ($^\circ$) | Fraction |
|----------------------|---------------------|--------------------|----------|
| $K_S\sigma_1$ | 1.57 ± 0.10 | 214 ± 4 | 9.8% |
| $K_S\rho^0$ | 1.0 (fixed) | 0 (fixed) | 21.6% |
| $K_S\omega$ | 0.0310 ± 0.0010 | 113.4 ± 1.9 | 0.4% |
| $K_S f_0(980)$ | 0.394 ± 0.006 | 207 ± 3 | 4.9% |
| $K_S\sigma_2$ | 0.23 ± 0.03 | 210 ± 13 | 0.6% |
| $K_S f_2(1270)$ | 1.32 ± 0.04 | 348 ± 2 | 1.5% |
| $K_S f_0(1370)$ | 1.25 ± 0.10 | 69 ± 8 | 1.1% |
| $K_S\rho^0(1450)$ | 0.89 ± 0.07 | 1 ± 6 | 0.4% |
| $K^*(892)^+\pi^-$ | 1.621 ± 0.010 | 131.7 ± 0.5 | 61.2% |
| $K^*(892)^-\pi^+$ | 0.154 ± 0.005 | 317.7 ± 1.6 | 0.55% |
| $K^*(1410)^+\pi^-$ | 0.22 ± 0.04 | 120 ± 14 | 0.05% |
| $K^*(1410)^-\pi^+$ | 0.35 ± 0.04 | 253 ± 6 | 0.14% |
| $K_0^*(1430)^+\pi^-$ | 2.15 ± 0.04 | 348.7 ± 1.1 | 7.4% |
| $K_0^*(1430)^-\pi^+$ | 0.52 ± 0.04 | 89 ± 4 | 0.43% |
| $K_2^*(1430)^+\pi^-$ | 1.11 ± 0.03 | 320.5 ± 1.8 | 2.2% |
| $K_2^*(1430)^-\pi^+$ | 0.23 ± 0.02 | 263 ± 7 | 0.09% |
| $K^*(1680)^+\pi^-$ | 2.34 ± 0.26 | 110 ± 5 | 0.36% |
| $K^*(1680)^-\pi^+$ | 1.3 ± 0.2 | 87 ± 11 | 0.11% |
| nonresonant | 3.8 ± 0.3 | 157 ± 4 | 9.7% |

Table 1: Results of the fit to determine the D decay model.

the selection efficiency is 6.2%, there are 69 candidates satisfying all selection criteria of which 58 ± 8 are found to be signal events. The Dalitz plot distributions of candidate events are also shown in Fig. 2. The Dalitz plot distributions of the different background sources are obtained using sideband regions in data or Monte Carlo simulation.

3.3 Extraction of ϕ_3

In order to test the analysis procedure, we use control samples of $B^\pm \rightarrow D^{(*)}\pi^\pm$; these have similar topology and phenomenology to our signal, but in this case the ratio of amplitudes is expected to be small ($r \sim 0.01$). We obtain results which are consistent with expectation, and take possible discrepancies into account in the systematic error.

We then perform unbinned maximum likelihood fits to the $B^\pm \rightarrow D^{(*)}K^\pm$ samples. In order to extract the three free parameters ϕ_3 , r and δ , we fit the B^+ and B^- samples simultaneously. However, to display the result, as in Fig. 3, we show likelihood contours in $(\text{Re}(re^{i\theta_\pm}), \text{Im}(re^{i\theta_\pm}))$, that are obtained separately for B^+ and B^- . CP violation is seen as a difference between the B^+ and B^- contours.

Since the value of r is positive definite, and the uncertainty on ϕ_3 depends on r , we do not rely on the errors obtained from the likelihood curves [22], but instead use a frequentist approach to obtain confidence regions, which are also shown in Fig. 3. The results for $B^\pm \rightarrow DK^\pm$ are

$$\begin{aligned}
\phi_3 &= 64^\circ \pm 19^\circ(\text{stat}) \pm 13^\circ(\text{syst}) \pm 11^\circ(\text{model}), \\
r &= 0.21 \pm 0.08(\text{stat}) \pm 0.03(\text{syst}) \pm 0.04(\text{model}), \\
\delta &= 157^\circ \pm 19^\circ(\text{stat}) \pm 11^\circ(\text{syst}) \pm 21^\circ(\text{model}),
\end{aligned} \tag{3}$$

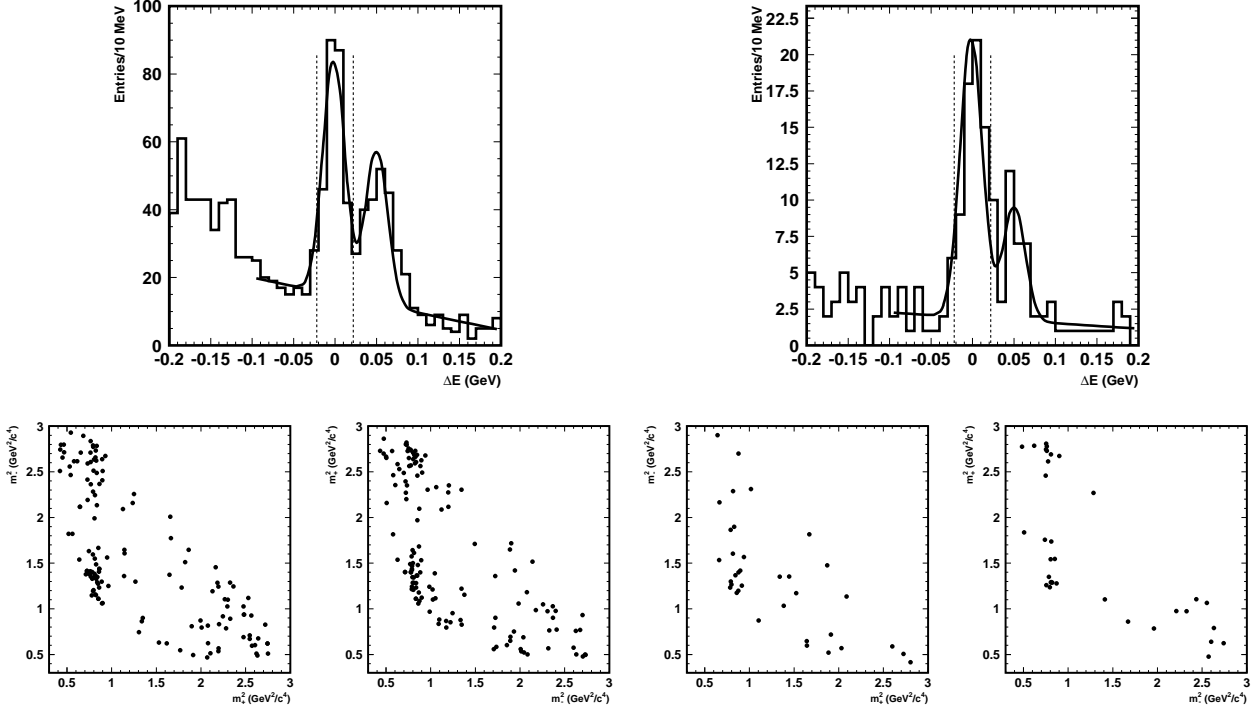


Figure 2: (Top) ΔE distributions and fit results for (left) $B^\pm \rightarrow DK^\pm$ and (right) $B^\pm \rightarrow D^*K^\pm$ candidates. (Bottom) Dalitz plots for (from left to right) $B^+ \rightarrow DK^+$, $B^- \rightarrow DK^-$, $B^+ \rightarrow D^*K^+$ and $B^- \rightarrow D^*K^-$ candidates. The axes are exchanged between B^+ and B^- candidates so that CP violation effects appear as differences between the B^+ and B^- distributions.

which correspond to $r > 0$ at 99.3% CL and CP violation at 94% CL. The results for $B^\pm \rightarrow D^*K^\pm$ are

$$\begin{aligned}\phi_3 &= 75^\circ \pm 57^\circ(\text{stat}) \pm 11^\circ(\text{syst}) \pm 11^\circ(\text{model}), \\ r &= 0.12^{+0.16}_{-0.11}(\text{stat}) \pm 0.02(\text{syst}) \pm 0.04(\text{model}), \\ \delta &= 321^\circ \pm 57^\circ(\text{stat}) \pm 11^\circ(\text{syst}) \pm 21^\circ(\text{model}),\end{aligned}\tag{4}$$

which correspond to $r > 0$ at 56% CL and CP violation at 38% CL. The dominant systematic uncertainty is due to possible fit bias (note again that more details can be found in [21]).

To combine the results from both modes we use a frequentist approach with Feldman-Cousins ordering and obtain

$$\phi_3 = 68^\circ {}^{+14^\circ}_{-15^\circ}(\text{stat}) \pm 13^\circ(\text{syst}) \pm 11^\circ(\text{model}),\tag{5}$$

which corresponds to CP violation at 98% CL. The two standard deviation interval including systematic and model uncertainties is $22^\circ < \phi_3 < 113^\circ$.

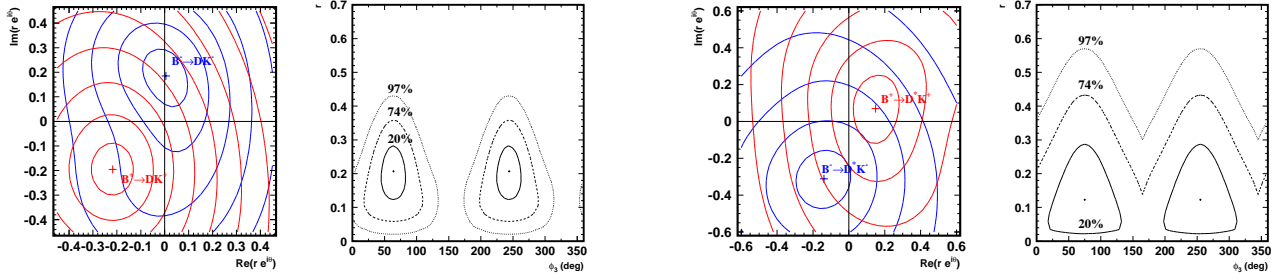


Figure 3: Likelihood contours for (left) $B^\pm \rightarrow DK^\pm$ and (right) $B^\pm \rightarrow D^*K^\pm$ candidates. In each pair, the leftmost plot is the result of the unbinned fit, and the rightmost is the outcome of the frequentist treatment, as described in the text.

4 Summary

The most precise measurement of ϕ_3 is presented. The value is consistent with the previous measurements from Belle [19] and BaBar [20]. We obtain a significantly smaller statistical error than BaBar due to the larger value of r obtained (there is, however, no significant discrepancy in the values of r obtained from these and other measurements [23]).

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